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LOCALIZATION OF FERMIONIC FIELDS ON BRANEWORLDS WITH BULK TACHYON MATTER

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Recently, Pal and Skar in [arXiv:hep-th/0701266] proposed a mechanism to arise the warped braneworld models from bulk tachyon matter, which are endowed with a thin brane and a thick brane. In this framework, we investigate localization of fermionic fields on these branes. As in the 1/2 spin case, the field can be localized on both the thin and thick branes with inclusion of scalar background. In the 3/2 spin extension, the general supergravity action coupled to chiral supermultiplets is considered to produce the localization on both the branes as a result.

Keywords: Braneworlds; Fermion zero modes.

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1. introduction

Extra dimensions were introduced to solve classical problems of Particle Physics. In the 1920's, Kaluza and Klein [1,2] proposed a theory with a compact fifth dimension to unify electromagnetism with Einstein gravity. Ref. 3 contains the first proposal for using large extra dimensions in the Standard Model with gauge fields in the bulk and matter localized on the orbifold fixed points (although the word brane was not used). In the course of the last few years there has been some considerable activity in the study of models that involve new extra spatial dimensions. [4,5,6,7] Recent years have been witnessing a phenomenal interest in the possibility that our observable four-dimensional (4D) Universe may be viewed as a hypersurface (brane) embedded in a higher-dimensional bulk space with non-factorizable warped geometry. [8,9,10,11] In this scenario, we are free from the moduli stabilization problem in the sense that the internal manifold is noncompact and does not need to be compactified to the Planck scale any more, which is one of reasons why this new compactification scenario has attracted so much attention.

Physical matter fields are confined to this hypersurface, while gravity can propagate in the higher-dimensional space-time as well as on the brane. A major issue in the so-called braneworld models is the localization problem[12−25] of the Standard

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Model fields on the brane. The most popular model in the context of brane world theory is that proposed by Randall and Sundrum (RS model).[6,7] The localization mechanism has been widely investigated in the RS model in five dimensions: Spin 0 field is localized on a brane with positive tension.[26] Spin 1 field is not localized neither on a brane with positive tension nor on a brane with negative tension.[27] Spin 1/2 and 3/2 fields are localized not on a brane with positive tension but on a brane with negative tension.[12] The general observation is that the graviton, which is allowed to be free to propagate in the bulk, are confined to the brane because of the warped geometry, the massless scalar fields have normalizable zero modes on branes of different types,[26] the Abelian vector fields are not localized in the RS model in five dimensions but can be localized in some higher-dimensional generalizations of it,[28] however, the fermions do not have normalizable zero modes both in five dimensions[26] and on a string[29,30] in six dimension.[9]

In most of the models, the induced metric on the brane is scaled Minkowski, i.e., the brane is flat. A few braneworld models considered the curvature of the embedded brane, some of which study the scenario with a FRW metric.[31,32] What turns out is that none of the braneworld models compatible to a FRW metric on the brane could provide an warped geometry. However, recently Ref. 33 proposed an exact, warped braneworld model arose from tachyon matter, falling in the class of exact higher dimensional warped spacetimes. The bulk Einstein equations can be exactly solved to obtain warped spacetimes. The solutions thus derived are single brane models–one being a thin brane while the other is of the thick variety. But they can not explain the problem of fermionic localization. Why the spin 1/2 field can be localized on the thick brane but not on the thin brane? What can we do to have it localized on both the branes? And how about the spin 3/2 field?

Based on this new braneworld scenario, we intend to investigate the localization of the spin 1/2 and 3/2 fermionic fields. We know that fermion interaction with a scalar domain wall can lead to localization of chiral fermions[34] and a Yukawa-type coupling to a scalar field of a domain-wall type can result in chirality as well as localization of the fermions.[35,36,37] It becomes necessary to allow additional non-gravitational interaction to get spinor fields confined to both the thin and the thick branes. The aim of the present article is to introduce dynamics to determine the localization of fermionic fields. We shall prove that spin 1/2 and 3/2 fields can be localized on both the branes.

2. The review of braneworld models arising from tachyon matter

In what follows, let us start with a brief review of the new braneworld models proposed by Ref. 33. Consider the action in five dimensional spacetime

$$S = \int d^5x \sqrt{-g} \left(\frac{1}{2\kappa_5^2}(R - 2\Lambda_5) + V(T)\sqrt{1 + g^{MN}\partial_M T \partial_N T} \right) + \lambda_b \int d^4x \sqrt{-\hat{g}},$$

(1)

where Λ_5, λ_b and $V(T)$ are the bulk cosmological constant, the brane tension and the potential of the tachyon field T, respectively, $\hat{g} = \det(\hat{g}_{\mu\nu})$ with $\hat{g}_{\mu\nu}$ being the induced metric on the brane. The first term in action (1) is the contribution from the pure 5D gravity and the tachyon field, and the second one is that from the brane. The FRW metric of the bulk spacetime is taken to be of the warped form

$$ds^2 = e^{2f(\sigma)}\hat{g}_{\mu\nu}(x)dx^\mu dx^\nu + d\sigma^2$$
$$= e^{2f(\sigma)}[-dt^2 + a^2(t)(dx^2 + dy^2 + dz^2)] + d\sigma^2, \tag{2}$$

where $a(t)$ is the scale factor and $f(\sigma)$ is the warp factor. Since the model is restrict to a de-Sitter brane, the scale factor can be expressed as $a(t) = e^{Ht}$ with H being the Hubble constant. Performing a conformal transformation $d\tau = a^{-1}(t)dt$, one can rewrite the bulk metric as

$$ds^2 = e^{2f(\sigma)}a^2(\tau)[-d\tau^2 + dx^2 + dy^2 + dz^2] + d\sigma^2. \tag{3}$$

For simplicity, the tachyon field can be chosen to have the form $T = T(t, \sigma)$. From the form of the Einstein tensors: $G_{MN} = -\Lambda_5 g_{MN} + \kappa_5^2 T_{MN}$, since there is no off-diagonal term, one could have either the time-derivative or the σ-derivative of the tachyonic field vanish. In this context, set the time-derivative of T to be zero, and choose the tachyon field T to be the form of $T(\sigma)$. Consequently, Einstein equations reduce to the following two coupled differential equations

$$3H^2 e^{-2f} - 6f'^2 - 3f'' = \Lambda_5 - \kappa_5^2 V(T)\sqrt{1 + T'^2} - \kappa_5^2\lambda_b\delta(\sigma - \sigma_0), \tag{4}$$

$$-6H^2 e^{-2f} + 6f'^2 = -\Lambda_5 + \kappa_5^2\frac{V(T)}{\sqrt{1 + T'^2}}, \tag{5}$$

in which σ_0 is the definite location of the brane. Given an expression for the tachyon potential $V(T)$, one can obtain a set of solutions for the above equations.

2.1. *The thin brane*

A thin brane is realized as a sharp peak of the warp factor at a definite location σ_0 in the entire range of the extra dimension. To get a thin brane, the contribution of the brane tension λ_b must be considered in the action. It is not required here to obtain the bulk geometry, so set $\Lambda_5 = 0$. Taking the tachyon potential as the form of

$$V(T) = \frac{3\sqrt{2}\kappa^2}{\kappa_5^2}\sin(\sqrt{2}\kappa|T|)[2 - \cos^2(\sqrt{2}\kappa|T|)]^{\frac{1}{2}} \tag{6}$$

and solving Eqs. (4) and (5), one can obtain the following expressions for the warp factor and the tachyon field

$$f(\sigma) = -\kappa|\sigma|, \tag{7}$$

$$T(\sigma) = \frac{1}{\sqrt{2}\kappa}\cos\left(\frac{\kappa}{H}e^{\kappa|\sigma|}\right). \tag{8}$$

One can see that the warp factor has discontinuous derivative at the brane location.

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2.2. *The thick brane*

For a thick brane, one need not consider the contribution from the brane tension. Hence, in this case, the intention is to solve the Einstein equations (4) and (5), with $\Lambda_5 \neq 0$ but $\lambda_b = 0$. The tachyon potential, expressed as a function of σ, is given by

$$V(\sigma) = \frac{1}{\kappa_5^2}\mathrm{sech}^2(b\sigma)\sqrt{(\Lambda_5 + 6b^2)\sinh^2(b\sigma) + \Lambda_5 + 6(b^2 - H^2)} \times \qquad (9)$$

$$\sqrt{(\Lambda_5 + 6b^2)\sinh^2(b\sigma) + (\Lambda_5 - 6H^2)},$$

where b is a certain arbitrary constant. Then, the exact expressions of $f(\sigma)$ and $T(\sigma)$ are solved to be

$$f(\sigma) = \ln\cosh(b\sigma), \qquad (10)$$

$$T(\sigma) = -\frac{i}{b}\sqrt{\frac{3(b^2 + H^2)}{\Lambda_5 - 6H^2}}\mathrm{EllipticF}\left[ib\sigma, \frac{\Lambda_5 + 6b^2}{\Lambda_5 - 6H^2}\right]. \qquad (11)$$

These special solutions would be utilized to analyse localization of fermionic fields on these branes in the next section.

3. Localization of Spin 1/2 Fermions

In this section we investigate localization of a spin 1/2 fermionic field. Let us consider the Dirac action of a massless spin 1/2 fermion in five dimension

$$S_{1/2} = \int d^5x\sqrt{-g}\bar{\Psi}\Gamma^M D_M\Psi, \qquad (12)$$

from which the Dirac equation is given by

$$\gamma^{\bar{M}}E_{\bar{M}}^M(\partial_M + \omega_M - ieA_M)\Psi = 0, \qquad (13)$$

where the indices of 5D coordinates are labeled with Latin letters $M, N, ...$ while $\bar{M}, \bar{N}, ...$ denote the local lorentz indices. Γ^M and $\gamma^{\bar{M}}$ are the curved gamma matrices and the flat ones, respectively, which are connected by the relation $\Gamma^M = E_{\bar{M}}^M\gamma^{\bar{M}}$ with $E_{\bar{M}}^M$ being the vielbein, $\omega_M = \frac{1}{4}\omega_M^{\bar{M}\bar{N}}\gamma_{\bar{M}}\gamma_{\bar{N}}$ is the spin connection, and A_M is a U(1) gauge field. In this model, we consider the special case with $A_M = 0$. The spin connection $\omega_M^{\bar{M}\bar{N}}$ in the covariant derivative $D_M\Psi = (\partial_M + \frac{1}{4}\omega_M^{\bar{M}\bar{N}}\gamma_{\bar{M}}\gamma_{\bar{N}})\Psi$ is defined as

$$\omega_M^{\bar{M}\bar{N}} = \frac{1}{2}E^{N\bar{M}}(\partial_M E_N^{\bar{N}} - \partial_N E_M^{\bar{N}})$$

$$- \frac{1}{2}E^{N\bar{N}}(\partial_M E_N^{\bar{M}} - \partial_N E_M^{\bar{M}})$$

$$- \frac{1}{2}E^{P\bar{M}}E^{Q\bar{N}}(\partial_P E_{Q\bar{R}} - \partial_Q E_{P\bar{R}})E_M^{\bar{R}}. \qquad (14)$$

In terms of Eqs. (3) and (14), the non-vanishing components of ω_M are

$$\omega_\mu = \frac{1}{2}f'(\sigma)\Gamma_\mu\Gamma_\sigma + \hat{\omega}_\mu, \qquad (15)$$

where $\mu = 0, 1, 2, 3$ and $\hat{\omega}_\mu = \frac{1}{4}\bar{\omega}_\mu^{\bar{\mu}\bar{\nu}}\Gamma_{\bar{\mu}}\Gamma_{\bar{\nu}}$ is the spin connection derived from the metric $\hat{g}_{\mu\nu}(x) = \hat{e}_\mu^{\bar{\mu}}\hat{e}_\nu^{\bar{\nu}}\eta_{\bar{\mu}\bar{\nu}}$. The Dirac equation (13) becomes

$$\left\{\Gamma^\mu\left(\hat{D}_\mu + \frac{1}{2}f'(\sigma)\Gamma_\mu\Gamma_\sigma\right) + \Gamma^\sigma\partial_\sigma\right\}\Psi = 0, \tag{16}$$

where $\hat{D}_\mu = \partial_\mu + \hat{\omega}_\mu$ is the Dirac operator on the brane.

Now, considering the conditions $\Gamma^\sigma = \gamma^\sigma$ and $\gamma^\sigma\Psi = \Psi$, from the above equation, we can obtain the solutions of the form $\Psi(x^M) = \psi(x^\mu)U(\sigma)$, where $U(\sigma)$ satisfies

$$(\partial_\sigma + 2f'(\sigma))\,U(\sigma) = 0, \tag{17}$$

i.e.

$$U(\sigma) = U_0\,e^{-2f(\sigma)}. \tag{18}$$

Substituting the solution back into the 5D Dirac equation in curved space, Ref. 33 has shown that the integral of the Dirac action (12) diverges for the thin brane model whereas it is finite for the thick brane model. Now let us include a real scalar field ϕ in order to solve this problem. The modification of the Dirac action will be through some Yukawa term, with the coupling λ

$$S_{1/2} = \int d^5x\sqrt{-g}[\bar{\Psi}\Gamma^M(\partial_M + \omega_M)\Psi + \lambda\bar{\Psi}\phi\Psi], \tag{19}$$

and the corresponding equation of motion is

$$\left\{\Gamma^\mu\left(\hat{D}_\mu + \frac{1}{2}f'(\sigma)\Gamma_\mu\Gamma_\sigma\right) + \Gamma^\sigma\partial_\sigma + \lambda\phi(\sigma)\right\}\Psi = 0. \tag{20}$$

The detail of the ϕ-field dynamics will not be important for our discussion. Imposing the relation $\Gamma^\sigma = \gamma^\sigma$ and the chirality condition $\gamma^\sigma\Psi = +\Psi$, we only need to solve

$$(\partial_\sigma + 2f'(\sigma) + \lambda\phi(\sigma))\,U(\sigma) = 0. \tag{21}$$

The solution of the above equation is turned out to be

$$\Psi(x^M) = U_0 e^{-2f(\sigma) - \lambda\int^\sigma \phi(\sigma)d\sigma}\psi(x^\mu). \tag{22}$$

In terms of this new variable, the action (19) can be rewritten as

$$S_{1/2} = U_0^2\int_0^\infty d\sigma\,e^{-f(\sigma) - 2\lambda\int^\sigma \phi(\sigma)d\sigma}\int d^4x\sqrt{-\hat{g}}\bar{\psi}\gamma^\mu(\partial_\mu + \hat{\omega}_\mu)\psi. \tag{23}$$

In order to localize spin 1/2 fermion in this framework, the integral (23) should be finite. In fact, the requirement is easily satisfied. Now let us look for the condition for localization of spin 1/2 field. For example, we shall only assume that the ϕ field equation of motion admits a localized σ-dependent solution such that $\phi(\sigma) \to |v|\epsilon(\sigma)$ as $|\sigma| \to \infty$, where $v = \langle\phi\rangle$, and $\epsilon(\sigma)$ is the sign function i.e.

$$\phi(\sigma) = |v|\epsilon(\sigma). \tag{24}$$

Once again the second integral leads to the Dirac equation in curved spacetime on the brane. So, a finite value for the first integral involving σ will guarantee that the

zero mode of a spin 1/2 field is localized on the branes. One can readily show that for large enough values of $\lambda|v|$, this integral (23) is finite for both the thin brane and the thick brane. For the thin brane, it is sufficient to have $\lambda|v| > \frac{\kappa}{2}$. We can choose the form as follows

$$\phi(\sigma) = c\sigma^n, \tag{25}$$

where $c > 0$ is the arbitrary constant and n satisfies $n \geq 1$. We can also choose the form

$$\phi = e^{c\sigma}, \tag{26}$$

where c is the arbitrary positive constant. So spin 1/2 field is localized on both the branes under condition (24) or (25) or (26). Of course, there are many other choices which result in a finite action.

4. Localization of Spin 3/2 Fermions

Next we turn to a spin 3/2 field, i.e. the gravitino. Let us start by considering the general supergravity action coupled to chiral supermultiplets[38]

$$S_{sg} = \int d^5 x \sqrt{-g} \frac{1}{2\kappa_5^2} R - \int d^5 x \sqrt{-g} G_j^i g^{MN} D_M \phi_i D_N \phi^{*j}$$

$$+ \int d^5 x \sqrt{-g} \bar{\Psi}_M i \Gamma^{[M} \Gamma^N \Gamma^{R]} \{ D_N \Psi_R + i\lambda \Gamma^\sigma (G^i D_N \phi_i - G_i D_N \phi^{*i}) \Psi_R \} + \ldots \tag{27}$$

where $D_N \phi_i = \delta_N^\sigma \partial_\sigma \phi_i$, λ denotes the coupling constant, the indices i, j represent the number of the scalar fields, and the square bracket on the curved gamma matrices Γ^M denotes the anti-symmetrization with weight 1. The function G is the Kahler potential $G(\phi^*, \phi) = -3\log(-\frac{K(\phi^*,\phi)}{3}) + \log|W(\phi)|^2$, with a general function K and the superpotential W. Without loss of generality, the expression $K = -3\exp(-\phi^*\phi/3)$ can be chosen. Moreover, various derivations of the Kahler potential are defined as

$$G^i = \frac{\partial G}{\partial \phi_i}, \ \ G_i = \frac{\partial G}{\partial \phi^{*i}} \ \ G_j^i = \frac{\partial^2 G}{\partial \phi_i \partial \phi^{*j}}. \tag{28}$$

The equations of motion for the Rarita-Schwinger gravitino field are derived as

$$\Gamma^{[M} \Gamma^N \Gamma^{R]} (D_N + i\lambda \Gamma^\sigma \delta_N^\sigma \phi^* \overleftrightarrow{\partial_\sigma} \phi) \Psi_R = 0. \tag{29}$$

Here $D_N \Psi_R = \partial_N \Psi_R - \Gamma_{NR}^M \Psi_M + \omega_N \Psi_R$ and $\phi^* \overleftrightarrow{\partial_\sigma} \phi = \phi^* \partial_\sigma \phi - \partial_\sigma \phi^* \phi$, which is defined with the affine connection $\Gamma_{MN}^R = E_M^R (\partial_M E_N^{\bar{M}} + \omega_M^{\bar{M}\bar{N}} E_{N\bar{N}})$. With the non-vanishing components of spin connection and affine connection

$$\omega_\mu = \frac{1}{2} f'(\sigma) \Gamma_\mu \Gamma_\sigma + \hat{\omega}_\mu, \tag{30}$$

$$\Gamma_{\mu\sigma}^\nu = f'(\sigma) \delta_\mu^\nu,$$

$$\Gamma_{\mu\nu}^\sigma = -a^2(\tau) e^{2f(\sigma)} \eta_{\mu\nu},$$

the components of the covariant derivative are calculated as follows

$$D_\mu \Psi_\nu = \partial_\mu \Psi_\nu + a^2(\tau)e^{2f(\sigma)}\eta_{\mu\nu}\Psi_\sigma + \frac{1}{2}f'(\sigma)\Gamma_\mu\Gamma_\sigma\Psi_\nu + \hat{\omega}_\mu\Psi_\nu, \tag{31}$$

$$D_\mu \Psi_\sigma = \partial_\mu \Psi_\sigma - f'(\sigma)\delta_\mu^\nu \Psi_\nu + \frac{1}{2}f'(\sigma)\Gamma_\mu\Gamma_\sigma\Psi_\sigma + \hat{\omega}_\mu\Psi_\sigma, \tag{32}$$

$$D_\sigma \Psi_\mu = \partial_\sigma \Psi_\mu - f'(\sigma)\delta_\mu^\nu \Psi_\nu. \tag{33}$$

According to the assumption $\Psi_\sigma = 0$, we will look for the solutions of the form

$$\Psi_\mu(x,\sigma) = \psi_\mu(x)U(\sigma), \tag{34}$$

where $\psi_\mu(x)$ satisfies the following equations $\gamma^\nu\psi_\nu = \partial^\mu\psi_\mu = \gamma^{[\mu}\gamma^\nu\gamma^{\rho]}\hat{D}_\nu\psi_\rho = 0$ and $\Gamma^\sigma\psi_\mu = \psi_\mu$. Then the equations of motion (29) reduce to

$$(\partial_\sigma + f'(\sigma) + i\lambda\phi^*\overleftrightarrow{\partial_\sigma}\phi)U(\sigma) = 0, \tag{35}$$

from which $U(\sigma)$ is easily solved to be

$$U(\sigma) = U_0 e^{-f(\sigma)-i\lambda\int^\sigma \phi^*\overleftrightarrow{\partial_\sigma}\phi d\sigma}. \tag{36}$$

To this end, let us substitute the zero mode (36) into the action (27) and consider that $i\lambda\phi^*\overleftrightarrow{\partial_\sigma}\phi$ is real. It turns out that the action of the Rarita-Schwinger gravitino field becomes

$$S_{3/2} = \int d^5x\sqrt{-g}\,i\bar{\Psi}_M\Gamma^{[M}\Gamma^N\Gamma^{R]}(D_N + i\lambda\Gamma^\sigma\delta_N^\sigma\phi^*\overleftrightarrow{\partial_\sigma}\phi)\Psi_R$$
$$= U_0^2\int_0^\infty d\sigma e^{-f(\sigma)-2i\lambda\int^\sigma \phi^*\overleftrightarrow{\partial_\sigma}\phi d\sigma}\int d^4x\sqrt{-\hat{g}}\,i\bar{\psi}_\mu\gamma^{[\mu}\gamma^\nu\gamma^{\rho]}\hat{D}_\nu\psi_\rho. \tag{37}$$

A finite value for the first integral will guarantee that the zero mode of a spin $3/2$ field is localized on the brane. The requirement is easily satisfied. We shall assume that the ϕ field satisfies

$$\phi = |v|e^{i|\sigma|}, \tag{38}$$

where v is a constant, then

$$i\lambda\phi^*\overleftrightarrow{\partial_\sigma}\phi = -2\lambda|v|^2\epsilon(\sigma). \tag{39}$$

When $\lambda < -\frac{\kappa}{4|v|^2}$, the integral (37) is finite for the thin brane model with decreasing warp factor $f(\sigma) = -\kappa|\sigma|$, and it is also finite for the thick brane model with increasing warp factor $f(\sigma) = \ln\cosh(b\sigma)$. Thus, it turns out that the zero mode of the gravtino field can be localized on both the thick brane and the thin brane.

5. Conclusion

Since spin half fields can not be localized on both the branes by gravitational interaction only, it becomes necessary to introduce additional non-gravitational interaction to get spinor field confined to both the branes. In the braneworld model arising from tachyon matter, we introduce dynamics which can determine the location of the branes in the bulk.

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In the spin 1/2 field, we introduce the scalar ϕ by involving the Yukawa coupling. We obtain the general form (23), which generalized the conclusion drew by 35. By choosing the appropriate values of the scalar field ϕ and the coupling constant λ, the action (23) can be finite on both the branes. That is to say, the spin 1/2 field can be localized not only on the thick brane but also on the thin brane. It has been proved that many choices can make the action finite. In this paper, we only give the conditions (24), (25), (26) as examples.

For the spin 3/2 field, i.e., the Rarita-Schwinger gravitino field, we consider the supergravity action coupled to the chiral supermultiplets and obtain the general form of the action (37). It is proved that under the condition (38), the action can be finite, i.e., the spin 3/2 fields also can be localized on both the thin brane and the thick brane.

Moreover, to localize the fermions on the brane or the string-like defect, there are some other backgrounds could be considered besides scalar field and gravity, for example, gauge field[22,39] or vortex[40,41,42] and gravity backgrounds. The localization of the topological Abelian Higgs vortex coupled to fermion can be fund in our another work.[43]

Acknowledgments

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